ENVIRONMENT, EQUITY AND WATERSHED MANAGEMENT

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Abstract

This paper presents a methodology for incorporating environmental and social equity objectives in an economic analysis of watershed management. Empirical results indicate that restricting agricultural pollution notably increases farm costs. The equity objective also adversely affects economic efficiency, but the cost increase due to social equity is less significant.

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Introduction

Agriculture is the leading cause of environmental degradation and pollution in most waterways, lakes and aquifers. Runoff from agricultural land transports eroded soil, fertilizers, pesticides, and sometimes pathogens. In many cases, surface and groundwater pollution levels exceed the standards set by environmental regulations. For instance, Lake Pittsfield in west central Illinois has lost 25% of its water storage capacity due to sedimentation, while the concentration of atrazine in the lake water has reached 13 ppb during some peak runoff seasons, well above the drinking water standard of 3.0 ppb. At present, economically feasible water treatment alternatives are not available, but the use of environmentally sound agricultural production practices in the watershed have the potential to control this phenomenon.

Research results indicate that pollution can be significantly reduced through various measures including tillage practices, crop and rotation choices, and switching to alternative chemical mixes.[1] Some studies have found that pollution control alternatives may yield both economic and environmental gains (Setia and Magleby), but this cannot be generalized. In most cases, conservation practices increase the demand for chemicals which adversely affects pollution and farm profitability (Zilberman and Marra; Insensee and Sadeghi). Moreover, environmental

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[1] For instance, switching from continuous corn or corn-soybean rotation to corn-alfalfa rotation may reduce erosion by 40%. Similarly, corn-soybean rotation may reduce nitrogen runoff by 10-30% relative to continuous corn alternative. No-till systems can reduce nitrogen runoff by 24% when compared to conventional tillage. Herbicide runoff can be reduced by about 70% with no-till and mulch-till practices whereas over 40% reduction can be obtained with ridge-till (Mellerowics et al.; Putman and Alt; Phillips et al.; Jones, Selley and Mielke; Prato et al.; Fawcett et al.; Insensee and Sadeghi).

objectives typically involve several attributes, all of which cannot be improved simultaneously.

Pollution issues in agriculture are best studied at the watershed level (Lowrance). Within a watershed, each farm's contribution to environmental degradation and the impacts of regulations will vary due, in part, to spatial differences in land and soil characteristics. Therefore, when exploring alternative options for watershed management, it may be necessary to spread the negative economic impacts of policy options as fairly as possible so that the socially desirable management strategies can be embraced by the participants. Conventional optimization approaches assume full cooperation and prescribe a resource allocation scheme that optimizes economic efficiency for the entire watershed. Such schemes usually entail highly specialized regional production patterns which may be inadmissible to individual groups.

The purpose of this paper is to develop a methodological framework that provides the capability to integrate economic and environmental objectives while incorporating equity among participants. This framework will be applied to the Lake Pittsfield watershed in west central Illinois. The analysis will determine the economic costs that result when atrazine, a widely used herbicide, can no longer be used within the watershed. The analysis will investigate the trade-off between equity and economic efficiency.

Methodology

A mathematical programming model is developed to address the above issues. The model determines spatial production alternatives, crop rotations, resource allocation and technology choices that maximize aggregate economic returns to the entire watershed while satisfying resource constraints, pollution standards, and equity goals. Resource constraints in mathematical programming models are customary. Pollution regulations are incorporated by using a chance-constrained programming formulation (Charnes and Cooper). These will be described later. The constraint imposing a minimum equity level, i.e., diversification of economic losses resulting from pollution regulation, is a novel methodological contribution of this paper. Therefore, this aspect of the model is elaborated below in some detail.

Diversity is a widely used concept in ecology (Magurran; Pielou; Weitzman; Solow, Polasky and Broadus). Different definitions have been introduced to measure different aspects of diversity (Magurran; Weitzman). Here, we focus on structural diversity that measures the degree of inequality between the entries (attributes) of an outcome vector. In the present context, the outcome vector consists of the economic losses realized by a group of farms resulting from environmental regulation. For instance, the outcome (1500,500,3000) assigns \$1500, \$500, and \$3000 losses to three farms. When compared with this outcome, the outcome vector (2000,1250,1750) is more diversified since the losses are more equally distributed among the three farms. In this simple example, the comparison is fairly straightforward. However, the Lake Pittsfield watershed consists of several subwatersheds, each of which will be represented by a farm. This complicates the inequality comparison. To cope with this difficulty, this paper introduces a diversity function, denoted by D(**x**), defined for an outcome vector $\mathbf{x}=(x_i)\in\mathbb{R}^n$ as follows:

$$\text{(1)} \qquad D(\mathbf{x}) = 1 - \frac{1}{2(n-1)} \frac{\sum_{i,j} |x_i - x_j|}{\sum_j x_j} = 1 - \frac{1}{n-1} \sum_{s_i<s_j} (s_j - s_i) \ ,$$

where $s_i = x_i / \sum x_j$. The second half of the above definition presents a useful perspective for interpreting what is being measured. Individual attributes are put on a diversity scale where each attribute is assigned a scalar index defined as the relative deviation from all other attributes having a higher relative share, i.e., $\sum(s_j - s_i)$ where $s_j > s_i$. The higher the scalar index, the more distant an attribute from the attributes above it in the hierarchy. The overall diversity is then defined as the average of diversity indices attached to individual attributes. The higher the diversity the more equal the distribution, and vice versa. D(**x**) attains its maximum value (1.0) when s_i=1/n for all i, and its minimum value (0.0) when s_i=1 for an attribute *i* while s_i=0 for all others (Önal). The diversity indices calculated for the two outcomes mentioned above are 0.5 and 0.85, respectively.

When determining management strategies aimed at economic efficiency, numerous alternative distributions of economic losses can occur, each implying a different social equity (diversity) index. At one end of the spectrum, there is absolute equity which assigns an equal loss to individual farms. This outcome may be associated with poor economic efficiency. At the other extreme, a single farm carries the entire loss, while all other farms achieve their unregulated net returns. This outcome may yield optimum economic efficiency, but with a poor diversity level. The approach used in this study is to maximize aggregate net return by systematically varying equity between the two extreme alternatives. This rules out the management alternatives which yield poorer economic returns or poorer equity among farm groups. An efficiency frontier will be obtained and trade-offs between economic and equity objectives will be investigated.

The Model

The notation used in the model is as follows: *n* is the number of representative farms; *f*, *j*, *k*, *i* are subscripts for representative farms, production activities (technology), land categories and commodities; p_i denotes product prices; $y_{i,f,k,j}$ denotes crop yields; $c_{i,f,k,j}$ denotes production costs per unit acreage; $A_{f,k}$ is land availability; I_f is maximum net returns without pollution regulation; $r_{i,f,k,j}$ is pollution (runoff) per unit acreage; e is the pollution standard; α is the equity index; β is the pollution safety level (probability); $\mathbf{L}=(L_f)$ is a vector of economic losses under pollution regulation; $\mathbf{U}=(U_{f,f'})$ and $\mathbf{V}=(V_{f,f'})$ are positive and negative deviation variables defined for the difference of loss variables for farms f and f'; and $\mathbf{X}=(X_{f,k,j})$ is a production activity vector. The symbols **L**, **U, V**, and **X** indicate endogenous variables. The algebraic model is as follows:

$$\text{(2)} \qquad \text{Max} \sum_{i,f,j,k} (p_i \, y_{i,f,j,k} - c_{i,f,j,k}) \, X_{i,f,j,k}$$

such that:

$$\text{(3)} \qquad \sum_{j} X_{i,f,j,k} \leq A_{f,k} \quad \text{for all f, k}$$

$$\text{(4)} \qquad L_f = I_f - \sum_{i,j,k} (p_i \, y_{i,f,j,k} - c_{i,f,j,k}) \, X_{i,f,j,k} \qquad \text{for all f}$$

$$\text{(5)} \qquad L_f - L_f^{\prime} = U_{f,f'} - V_{f,f'} \quad \text{for all f, f}'$$

$$\text{(6)} \qquad \sum_{f,f'} (U_{f,f'} + V_{f,f'}) \leq 2(1-\alpha)(n-1) \sum_{f} L_f$$

$$\text{(7)} \qquad \sum_{f,j,k} r_{i,f,j,k} X_{i,f,j,k} \leq -e/\ln(1-\beta)$$

$$\text{(8)} \qquad X_{i,f,j,k}, \; L_f \, , \; U_{f,f'}, \; U_{f,f'} \geq 0$$

The objective function (2) represents total net economic returns. Constraint (3) reflects land use balances. Equation (4) is an accounting expression that determines economic losses for the farms. Equation (5) expresses the difference of loss variables in terms of positive and negative deviation variables. Equation (6) is a linearized form of the equity constraint $D(\mathbf{X}) \geq \alpha$, where the left-hand side equals the sum of absolute differences $|L_f - L_{f'}|$. Details of the linearization technique can be found in Önal. Finally, equation (7) is a chance-constrained programming formulation that restricts total pesticide runoff.[2] Instead of the standard water pollution level e=3 ppb, (7) incorporates a lower limit so that the pollution will not exceed e with a probability greater than β. The expression on the right-hand side of (7) reflects the assumption that the stochastic nature of pesticide runoff can be represented as an exponentially distributed random variable.

Model Specification and Data

The model incorporates alternative crop rotations, tillage practices and input-use combinations for each land category and each subwatershed. The spatial variability of cropland within the watershed is captured with a geographic information system (GIS), which subdivides the watershed into fifty sub-basins based on hydrologic criteria. The sub-basins are then clustered into seven representative farms, with each farm defined by the cropland contained within these contiguous sub-basins. Using field-level data from the GIS, each farm is further partitioned into three distinct land types based on the inherent erodibility of the cropland: non-highly erodible land (NHEL), highly erodible land (HEL), and extremely erodible land (XHEL). The distribution of cropland by land type for each of the farms is shown in Table 1. Local conservation efforts to control soil erosion restrict the choice of tillage systems on certain land types. Cropland classified as XHEL is limited to the use of a no-till system when corn is grown, while HEL fields can use either a no-till or mulch-till system. Clean-till is an option only on NHEL cropland.

Several weed control strategies are identified which correspond to different levels of atrazine use: *normal, reduced,* and *zero*. Each strategy includes both a primary treatment and a secondary treatment. The primary treatment takes place either before or at planting, while the

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[2] Chemical loss from cropland is largely due to the occurrence of runoff-producing rainfall soon after the application. Therefore, runoff is a random event and depends on the underlying hydrologic processes determined by the timing and magnitude of runoff events.

secondary treatment occurs after the crop has emerged. Under the *normal* option, atrazine is used in the primary treatment at rates between 1.2 and 1.6 lbs of active ingredient per acre (depending on the tillage system used). In the *reduced* option, atrazine use is limited to secondary treatments at a rate just under one pound of active ingredient per acre. Atrazine is eliminated entirely in the *zero* option. Given the recent decision to discontinue the production of cyanazine (a popular low-cost alternative to atrazine), non-cyanazine alternatives for the *reduced* and *zero* options were also identified. The different weed control strategies are summarized in Table 2.

Each farm's contribution to the pollution potential in the lake water will depend on three factors: 1) the choice of tillage system, crop rotation, and level of atrazine use on each land type, 2) the distribution of soils across land types, and 3) the number of acres of each land type being farmed. For the sake of space, the methodology and models used to estimate farm-level yields, costs, and atrazine runoff parameters will not be discussed in detail.[3]

Results

The model is first run without imposing the pollution and equity constraints, and under the

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[3] The modeling technique used to develop atrazine runoff parameters includes: 1) a *field-scale biophysical simulation model (EPIC,* Williams et al*.)* which generates event-specific data relating farm management practices and soil properties to edge-of-field runoff losses; 2) a *regression metamodel* that uses regression analysis to explain the observed relationships between farming practices, soil properties, rainfall patterns, and surface runoff losses that were generated with the field-scale biophysical simulation model; 3) a *pesticide transport model* (Haith) for predicting pesticide losses from a series of runoff events following application; and 4) a *dynamic watershed response model* that integrates the spatial representation of the watershed with the pesticide loss algorithm to predict aggregate watershed response to various weed control practices when subject to stochastic rainfall patterns.

assumption that cyanazine is available. The results presented in Table 3 show that it is optimal for all farms to use a corn-soybean rotation on all land categories. About 83% of the total corn acreage uses the mulch-till option while the remaining corn acreage uses no-till on XHEL cropland. Clean-till is not used on any land category. All farms apply the *normal* herbicide option for producing corn, as expected. For soybeans, no-till is the only tillage system used. This result defines the unrestricted optimum for production and resource allocation, which will be referred to as the *base case* in the remaining of the paper.

The model is then solved by augmenting the pollution constraint (7) to the base case formulation, with a pollution safety level of β=0.99. Once again the corn-soybean rotation is the optimum rotation alternative (Table 4). However, two important changes are observed relative to the base case. First, a substantial shift to clean-till occurs; 1,163 acres of NHEL cropland shifts to clean-till, representing 65% of the total corn acreage. This shift to clean-till occurs because of the reduced potential for atrazine runoff following soil incorporation. No-till corn production remains the same (302 acres), while mulch-till is used on 321 acres of HEL cropland. The second important change involves the choice of herbicide. Most of the clean-till corn acreage uses the normal (NORM) herbicide option, but a small fraction, about 7%, uses the zero (ZERO) option. On the HEL cropland, where mulch-till is used exclusively, the resulting shares of the three herbicide options are 151 acres (47%), 92 acres (29%), and 78 acres (24%) for normal (NORM), reduced (RED), and zero (ZERO), respectively. On XHEL cropland, most of the corn acreage, 237 acres (79%) uses the zero option, while the remaining 64 acres (21%) uses the normal option. The shift to zero and reduced herbicide options (a total of 484 acres) was necessary to satisfy the pollution constraint which was not imposed in the base run.

The aggregate income loss resulting from the environmental constraint would be approximately $13,200. These losses are not distributed equally among the farms, however. Two typical cases are shown in Figure 1. Farm-5 loses nearly $3,000 while the loss to Farm-1 is under $500. The overall equity level, as defined by equation (1), is 0.70 which suggests that only 70% of the absolute equity is achieved. Because of this unequal distribution of losses, the economically efficient production and weed control plan that maximizes total net return to the entire watershed may not be acceptable to the individual farms. The issue is, therefore, to investigate how the aggregate loss is affected when an improvement in equity is imposed. The overall trade-off curve in Figure 1 shows that slight losses in total income would occur throughout the equity range 0.70-0.91. The losses increase faster thereafter. Yet, the total cost of absolute equity, where all farms lose the same amount of income, is $14,600, which is only $1,400 more than the total loss at the 0.70 equity level. The trade-off curves for three of the seven farms are also shown in Figure 1. Farms 1 and 6 would experience an increase in income loss with greater levels of equity, suggesting that these farms are relatively more efficient at reducing atrazine losses than other farms. Income losses for Farm-5 decrease with increasing levels of equity, suggesting that this farm was shouldering an inequitable share of the abatement burden at economically efficient solution.

Conclusion

This paper introduces a methodology for incorporating environmental and social equity objectives in economic analysis, and presents an empirical application to a watershed in west central Illinois. Net economic returns to the entire watershed are maximized while restricting both the concentration of atrazine in the lake and the economic burden placed any one farm relative to group of farms within the watershed. The results indicated a notable cost increase due to the pollution restriction. The equity objective also adversely affects the aggregate loss, but the magnitude of this loss is relatively insignificant, approximately 10 percent greater than the loss realized due to the pollution regulation alone. Linear programming solutions typically indicate highly specialized resource allocation schemes which imply unequal allocation of benefits and losses. The results of this study indicate that both environmental and social equity objectives can be achieved at the expense of an additional, but relatively small, increase in cost. Although this solution is not as economically efficient as the linear programming solution, it may be more politically acceptable to the farms because of its fairness.

The analysis here focused only on pollution from a particular herbicide. Including restrictions on gross sedimentation would reduce the shift to the clean-till option and require the adoption of more expensive weed control systems. Therefore, the reported economic losses are underestimates of the true costs of regulations.

Table 1. Distribution of Cropland Acreage Among the Seven Representative Farms.

Farm ID	NHEL	HEL	XHEL	Total Cropland
1	269.2	71.9	0	341.1
2	341.8	235.3	43.0	620.1
3	422.6	30.5	92.2	545.3
4	436.1	99.4	164.9	700.4
5	505.4	68.0	163.6	737.0
6	124.3	54.4	38.9	217.6
7	216.8	82.4	100.9	400.1
Total	2,316.2	641.9	603.5	3,561.6

Notes: No-till involves planting directly into undisturbed residue from the previous crop. Mulch-till retains at least 30% residue cover after planting, while clean-till leaves less than 30 % residue cover after planting.

Table 2. Alternative weed control strategies (when cyanazine is unavailable).

Normal	Reduced	Zero
No-till		
Bicep II - EPP	Roundup + Dual - PP	Roundup + Dual - PP
Banvel - POS	Marksman - POS	Exceed - POS
Mulch-till		
Bicep II - PRE	Dual - PP	Roundup + Dual - PRE
Banvel - POS	Marksman - POS	Exceed - POS
Clean-till		
Bicep II - PPI	Dual - PPI	Dual - PPI
Banvel - POS	Marksman - POS	Exceed - POS
Cultivation/Rotary Hoe	Cultivation/Rotary Hoe	Cultivation/Rotary Hoe

Table 3. Optimum Production Activities by Farm (in acres): Without Regulation (Base Case)†

FARM	FIELD ERODIBILITY	ROTATION	TILLAGE		
			NOTILL	MTILL	CTILL
Farm 1	HEL	CO-SB	SB: 35.95	CO: 35.95	0
	NHEL	CO-SB	SB: 134.6	CO: 134.6	0
Farm 2	XHEL	CO-SB	SB: 21.49 CO: 21.49	0	0
	HEL	CO-SB	SB: 117.67	CO: 117.67	0
	NHEL	CO-SB	SB: 170.89	CO: 170.89	0
Farm 3	XHEL	CO-SB	SB: 46.08 CO: 46.08	0	0
	HEL	CO-SB	SB: 15.25	CO: 15.25	0
	NHEL	CO-SB	SB: 211.28	CO: 211.28	0
Farm 4	XHEL	CO-SB	SB: 82.43 CO: 82.43	0	0
	HEL	CO-SB	SB: 49.68	CO: 49.68	0
	NHEL	CO-SB	SB: 218.07	CO: 218.07	0
Farm 5	XHEL	CO-SB	SB: 81.81 CO: 81.81	0	0
	HEL	CO-SB	SB: 34.01	CO: 34.01	0
	NHEL	CO-SB	SB: 252.7	CO: 252.7	0
Farm 6	XHEL	CO-SB	SB: 19.45 CO: 19.45	0	0
	HEL	CO-SB	SB: 27.21	CO: 27.21	0
	NHEL	CO-SB	SB: 66.77	CO: 66.77	0
Farm 7	XHEL	CO-SB	SB: 50.45 CO: 50.45	0	0
	HEL	CO-SB	SB: 41.22	CO: 41.22	0
	NHEL	CO-SB	SB: 108.42	CO: 108.42	0

†Atrazine use for all corn acres in the base case is NORM.

Table 4. Optimum Production Activities (in acres) by Farm: After Banning Atrazine (β=99%)

FARM	FIELD ERODIBILITY	ROTATION	TILLAGE		
			NOTILL	MTILL	CTILL
Farm 1	HEL	CO-SB	SB: 35.95	CO: 35.95 (ZERO)	0
	NHEL	CO-SB	SB: 134.6	0	CO: 94.96 (NORM), 39.7 (ZERO)
Farm 2	XHEL	CO-SB	SB: 21.49 CB: 21.49 (ZERO)	0	0
	HEL	CO-SB	SB: 117.67	CO: 55.0 (NORM) 62.67 (RED)	0
	NHEL	CO-SB	SB: 170.89	0	CO: 170.89 (NORM)
Farm 3	XHEL	CO-SB	SB: 46.08 CO: 5.47 (NORM), 40.61 (ZERO)	0	0
	HEL	CO-SB	SB: 15.25	CO: 15.25 (ZER0)	0
	NHEL	CO-SB	SB: 211.28	0	CO: 211.28 (NORM)
Farm 4	XHEL	CO-SB	SB: 82.43 CO: 27.63 (NORM), 54.8 (ZERO)	0	0
	HEL	CO-SB	SB: 49.68	CO: 49.68 (NORM)	0
	NHEL	CO-SB	SB: 218.07	0	CO: 218.07 (NORM)
Farm 5	XHEL	CO-SB	SB: 81.81 CO: 31.2 (NORM), 50.6 (ZERO)	0	0
	HEL	CO-SB	SB: 34.01	CO: 34.01 (NORM)	0
	NHEL	CO-SB	SB: 252.7	CO: 252.7 (NORM)	0
Farm 6	XHEL	CO-SB	SB: 19.45 CO: 19.45 (ZERO)	0	0
	HEL	CO-SB	SB: 27.21	CO: 27.21 (ZERO)	0
	NHEL	CO-SB	SB: 66.77	0	CO: 29.33 (NORM), 37.44 (ZERO)
Farm 7	XHEL	CO-SB	SB: 50.45 CO: 50.45 (ZERO)	0	0
	HEL	CO-SB	SB: 41.22	CO: 12.37 (NORM), 28.86 (RED)	0
	NHEL	CO-SB	SB: 108.42	0	CO: 108.42 (NORM)

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